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Article

Measurement of the degree of connection between cities on the east and west banks of the Pearl River Estuary—Based on urban gravity model

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Abstract: Since the Reform and Opening up, GDP of the cities on eastern bank of the Pearl River Estuary in Guangdong Province were higher than the eastern bank cities. Therefore, this article aims to modify the urban gravity model combines it with the entropy weight method to calculate urban quality and applies it to measure the degree of connectivity between cities over the past decades. The research aims to explore whether cities with higher economic output have a greater attraction for surrounding cities, and whether the eastern bank cities can also promote the development of the west. Through detailed data collection and analysis, this essay reveals the dynamic changes of the gravity among cities and its influence factors such as economic, transportation and urban development. The research results indicate that the strongest gravitational force between cities on the east and west banks is between Dongguan and Zhongshan, rather than between Shenzhen and cities on the west bank. This demonstrates that the connection between cities on the east and west banks is primarily constrained by geographical factors, and the geographical location of a city influences on surrounding cities significantly. In particular, Dongguan and Zhongshan play a key role in connecting the eastern and western bank of the Pearl River Estuary, rather than Shenzhen, which is traditionally considered to have the highest economic aggregate. In addition, the study also found that the COVID-19 epidemic has had a significant impact on inter-city communication, resulting in a decline in inter-city gravity in recent years.

Keywords: gravity model; entropy weight method; economic connectivity

1. Research background

Urban gravity, as a multidimensional concept, has taken root in a variety of interdisciplinary fields including urban planning, economics, sociology, and geography. Meanwhile, it serves as an insightful perspective for exploring key issues such as urban development, population movement, resource allocation, and regional interaction. The research background presents a profound reflection on factors interplaying in urbanization process, influencing urban forms and functions, and driving sustainable urban development. owing to globalization and informatization in unprecedented pace, cities are no longer in isolation entities but have become nodes in a global network, leading to increasingly constant and close competition and cooperation between cities as economic bodies. Under the circumstance, urban gravity takes on a new norm; it not only pertains to a city's ability to attract population, capital, technology, and other production factors, but also involves its appeal in areas such as culture, innovation, and the environment. These factors collectively condition the overall competitiveness of cities.

The study of urban gravity is a revelation of the dynamics and mechanisms behind a city's ability to attract as well as retain various resources, including but not limited to its economic foundation industrial structure; in addition, there will be technological innovation, educational quality, quality of life, and policy environment. For example, economically developed cities often provide job opportunities and income levels, attracting a large influx of human resources. Meanwhile, cities with high-quality natural environments and well-developed infrastructure can attract more talent, further promoting knowledge innovation and social development.

In addition to this, urban gravity research will also be focusing on the possibility to strike a balance between urban development without compromising the carrying capacity of resource environments, exploring sustainable urban development models. With increasing emphasis on sustainable development goals, enhancing a city's green appeal—by improving the ecological environment and increasing resource utilization efficiency—has become a new research focus, making cities more livable and business-friendly (Jing, 2020).

In general, the study of urban gravity is an important exploration aimed at understanding the dynamics of urban growth, optimizing urban zoning, promoting cooperation between cities, and achieving sustainable urban development goals in the context of rapid global urbanization. It is significant not only for guiding urban planning and policy-making but also for fueling innovation in theories and methodologies across fields.

Guangdong in today's world economic dynamics

Guangdong, the forefront of China's reform and opening-up, takes off economically since 1978. As one of the most economically active provinces in China, Guangdong has rapidly risen to become a global manufacturing and trade hub, empowered by its advantageous geographical location, urban infrastructure, and reciprocal policies. The Pearl River Estuary region bears tremendous economic momentum and development potential. Located on the southern coast of China, the Pearl River Estuary is the mouth of the Pearl River and connects the core cities of the Pearl River Delta, including Guangzhou, Shenzhen, Dongguan, Zhuhai, Zhongshan, and Jiangmen. Therefore, it has become essential for both China and the world as a whole, leveraging the geographical advantages and abundant natural resources.

The economic growth of the cities on the both banks of the Pearl River Estuary, particularly Shenzhen, Dongguan, and Huizhou on the eastern bank, has always been a driving force for economic growth in Guangdong Province and even nationwide. According to reference materials, in 2022, Shenzhen's GDP reached 3.24 trillion RMB, while Dongguan and Huizhou's GDPs were 1.12 trillion and 540.1 billion RMB, respectively. These figures not only highlight the economic strength of the eastern bank cities but also secures the region's significant position in the national economic landscape. In contrast, cities on the western bank, such as Zhuhai, Zhongshan, and Jiangmen, although having relatively lower economic outputs, have also shown rapid growth in recent years. In 2022, Zhuhai's GDP was 404.5 billion RMB, Zhongshan's was 363.1 billion RMB, and Jiangmen's was 377.3 billion RMB. With the ongoing construction of the Guangdong-Hong Kong-Macao Greater Bay Area, the economic growth potential of the western bank cities is expected to be further unleashed.

Local governments usually prefer to pursue greater economic achievement and compete against each other because the official's promotion was obviously GDP performance-oriented (Li and Zhou, 2005). Thus, regional cooperation was rarely observed (Guo et al., 2021). Although the economic prosperity and high level of urbanization in the Pearl River Delta region, the development process has been characterized by a significant proportion of labor-intensive and heavily polluting industries. Additionally, there is a considerable disparity in economic development between urban areas and rural areas within the region. The income growth of rural residents' lags behind that of urban residents, and there are notable differences in rural infrastructure and public services compared to cities, which poses certain obstacles to regional economic integration (Yang and Yan, 2012).

2. Literature review

2.1. Origins and initial applications

The urban gravity model bases around Newton's law of universal gravitation, stating that objects of all kinds in nature are mutually gravitated. The gravitational force between two objects is proportional to the product in response to their masses and inversely proportional and in response to the square of the distance between them. Basing on this, in 1931, Reilly proposed the "retail gravity model," which formed the prototype of the gravity model.

2.2. International trade analysis

In 1962, Tinbergen and Pöyhönen applied the gravity model to the analysis of international trade (Shahriar et al., 2019), further deploying its application to a larger scale. According to this model, exports from country i to country j are explained by their economic sizes (GDP or GNP), their populations, direct geographical distances, and a set of dummies incorporating some type of institutional characteristics common to specific flows (Martinez-Zarzoso, 2003). In 1970, Leamer and Stern make one of the earliest attempts to derive a gravity equation based on the probability theory by arguing that the triumph of gravity equations is due mainly to incorporating trade demand and supply, thus excluding prices (Leamer and Stern, 1970). Later, Anderson applied Cobb–Douglas and constant elasticity of substitution (CES) production functions to successfully derive a standard theoretical gravity model based on Armington's assumption (Anderson, 1979), however, the model was not performed extensively among trade economists. After 1985, Bergstrand derived the gravity equation from the model by making certain assumptions (including perfect substitutability of international products). He believed that if trade flows are differentiated by origin, as the evidence suggests, then the typical gravity equation is incorrect, as it ignores certain price variables (Bergstrand, 1985; Kabir et al., 2017).

2.3. Time-varying characteristics of geographical systems

In 1999, Chen Yanguang argued that geographical systems differ from physical systems, suggesting that the urban gravity model should abandon instantaneous quantitative effects and introduce time-varying functions thus revise the model (Chen, 1999). This perspective extended the gravity model to dynamic changes in geographical systems. Although the article provided a modified gravity model, the article does not introduce sufficient empirical analysis to support the modified model.”

2.4. Multifactor comprehensive analysis

As research progresses, scholars then began to pour more factors into the gravity model to enhance its explanatory power for the sake of precision. In 2005, Cheng et al. set different equations into the gravity model to predict trade flows between regions, discovering that fixed effects models were statistically superior to other specifications, and the impact of integration on trade could vary significantly across different specifications (Cheng and Wall, 2005), Although the article conducted a thorough comparison and analysis of the fixed effect model, all models are based on a series of assumptions, such as the logarithmic linear relationship between trade volume and the negative impact of distance on trade volume. These assumptions may not fully hold in practical applications; and the article did not fully explore other factors that may affect trade volume, such as trade policy, cultural barriers, and institutions, which may influence the results of the gravity model. In 2006, Chen Peng, using the Liaoning urban circle as an example, introduced parameters such as urban functions, population corrections, and economic distance into a new urban gravity model, analyzing the main industries of Liaoning’s cities and identifying major urban center circles based on gravitational intensity (Chen, 2006). In 2013, Shi et al. introduced the Urban Attractiveness Inertia Index based on the urban gravity model and incorporated it into the urban attractiveness indicator system. They conducted hierarchical cluster analysis using SPSS and measured the gravitational pull of various cities in Shanxi Province based on the clustering speed of the results to delineate urban agglomerations. Although the study utilized cluster analysis to visualize the data, it was unable to demonstrate the direction of urban gravitational pull (Shi, 2013).

2.5. Adaptive evaluation and optimization analysis

In 2016, Hu Jinbao et al. constructed an adaptive evaluation index system based around economic, social, and transportation indicators, maximizing these indicators by using principal component analysis. They incorporated the optimized indicators into the urban gravity model and improved it to evaluate the Ningwu Expressway (Hu et al., 2016), However, it entertains doubts whether the Engel coefficient holds applicable to the life culture of Chinese in the selection of indicators, and the impact of highway operation on surrounding cities should capture adaptable consequences in the long run. In 2019, Lu Yan analyzed the development layout between provinces in the Sichuan, Guizhou, and Chongqing regions, identifying that development was conditioned by provincial capitals and secondary provincial capitals. Using principal component analysis, he introduced 18 indicators, including GDP and education funding, and converted the distances between cities into a time unit of 75 km/h; these were then analyzed within the urban gravity model to calculate the degree of connectivity among the major cities in these three regions (Lu, 2019).

2.6. Combining multiple analytical methods

In 2020, Tang Mingzhu et al. combined the gravity model with spatial autocorrelation analysis and another 11 indicators related to urban economy, population, and employment to measure urban comprehensive quality, focusing on the direction of gravitational attraction among cities while analyzing the economic space of the Fujian Triangle urban cluster (Tang et al., 2020). In 2021, Chen Jingjing et al. employed the entropy weight method to quantify indicator weights in the context of regional innovation polarization and connectivity in the Chengdu-Chongqing area, calculating a comprehensive index for the innovative development of the dual-city economic circle (Chen et al., 2021). In the same year, Fan et al. utilized various map navigation data to draw the regular traffic routes across Xi'an City and divided the city into different regions based on various economic data. They defined the spatial scope of the Xi'an metropolitan area from four perspectives, including urban gravity, thereby delineating the influence zones of Xi'an City. However, due to data limitations, many of the indicator data were not comprehensive (Fan, 2021). In 2024, Tang Kaiyang et al. revised the gravity model after calculating the comprehensive evaluation value of cities using the entropy weight method, quantifying the logistics connectivity strength between cities and considering the directional nature of this strength to calculate the overall connectivity intensity of one city to another, further assessing the cumulative influence of node cities within the logistics network (Tang et al., 2024).

However, the former studies have not been able to study the development of cities and cities over a long period of time according to the gravitational model, but only use one year's data to analyze the urban agglomeration. Based on this, the innovation of this paper is that the degree of connection between the cities on the east and west banks of the Pearl River Estuary is measured using ten -years data, in order to attempt to visualize the changes in the degree of connection between the cities of the east and west banks of the estuary.

3. Motivation and hypotheses

Unlike previous research, which was mainly aiming at analyzing interprovincial logistics and the Pearl River Delta as the Greater Bay Area with a significant lack of research on differentiation of development between the two banks of the Pearl River Estuary and on level of economic development, this study looks at the link between east bank and west bank cities to further measure the strength or weakness of gravity attraction between cities, complementing the above research gaps. At the same time, in the study of the relationship between the Pearl River Delta and the Greater Bay Area, the main use of principle component analysis. However, during actual data collection, we found that changes in statistical calibration would result in abnormal values in 2012 and 2013, and individual data for some cities would be far larger than in previous or subsequent years. It is because of the variance calculation used by PCA which will be too sensitive to outliers; thus, the calculation results will be biased. Entropy method is less affected by outliers. Considering the characteristics of small and medium sample data, entropy method is used to supplant PCA in this study. To study this problem, this paper measures the extent of the link between six cities on both sides.

Based on context above, this article comes up with the following three hypotheses:

Hypothesis 1: As economic special zones opened, Shenzhen and Zhuhai should be considered the hub cities on the eastern and western banks, respectively;

Hypothesis 2: The gravitational pull between cities on the same side should be stronger than that with cities on the opposite side;

Hypothesis 3: As the road networks between various cities in the Pearl River Delta continue to improve and the economy grows, the gravitational pull between cities should continually increase.

To address these questions, this article employs a modified urban gravity model combined with the entropy weight method to measure and analyze the degree of connectivity between the cities on the eastern and western banks of the Pearl River Estuary. There are parts of data which we show in **Table 1**.

Table 1. Indicators of years collected (excerpts).

Year	GDP (hundred million)	GDP Per capita	Traffic mileage (km)	Permanent population (ten thousands people)	Per capita disposable income (ten thousands yuan)	Passenger Volume (ten thousands people)	Freight Volume (ten thousands ton)	population density (people/km^2)	Urban land area (km^2)	Green coverage area (hectare)	Per capita green coverage area (m^2)	Number of Area
2020	27800	15.98	716	1763.4	6.49	13750	41483	6484	1997.47	101267	57.43	1
2021	30800	17.45	726	1768.2	7.08	13373	43690	6484	1997.47	100872	57.05	1
2022	32400	18.38	726	1766.18	7.27	10439	40893	8806	1997.47	101386	57.40	1
2020	9756	9.3194	5223	1048.36	5.65	831	17139	4262	2460	91728	87.50	2
2021	10931	10.401	5266.22	1053.68	6.21	899	17449	4283	2460	94912	90.08	2
2022	11200	10.6803	5266.22	1043.7	6.38	704	15115	4243	2460	95966	91.95	2
2020	4283.72	7.12	13447.2	605.72	3.97	926	21387	534	11347	12657	20.90	3
2021	5033.06	8.3	13516	606.6	4.33	889	24483	535	11350.36	12759	21.03	3
2022	5401.24	8.92	13491.7	605.02	4.49	577	21845	533	11350.36	13307	21.99	3
2020	3518	15.98	1472.6	244.96	5.59	2718	8294	1420	1725.07	32319	131.94	4
2021	3896	17.45	1472.6	246.67	6.14	2616	8886	1430	1725.07	34616	140.33	4
2022	4045	18.38	1505.2	247.72	6.30	1655	8148	1436	1725.07	34848	140.67	4
2020	3189	7.23	2731	443.11	6.49	530	10666	6484	1783	7367	16.63	5
2021	3578	8.04	2730	446.69	7.08	624	10661	6484	1783	7846	17.56	5
2022	3631	8.16	2830	443.11	7.27	441	9668	8806	1783	4610	10.40	5
2020	3200	6.70	9766.72	480.41	6.49	5127	17921	505	9506.92	21249	44.23	6
2021	3598	7.46	9828.05	483.51	7.08	1360	18568	507	9535.19	21333	44.12	6
2022	3773	7.81	9876.97	482.22	3.87	936	17805	506	9535.19	21800	45.21	6

Note: Number of Area:1: Shenzhen (SZ); 2: Dongguan (DG); 3: Huizhou (HZ); 4: Zhuhai (ZH); 5: Zhongshan (ZS); 6: Jiangmen (JM).

4. Research method

4.1. Gravity model

Due to the circumstance that strength of connections between cities varies and the need to measure the intensity of city-to-city connections from a spatial distance perspective, there are scholars having further refined the gravity model based on spatial decay theories in economics and geography. This model has explanation improved and the impact of economic factors on logistics networks specified, providing important insights for optimizing urban logistics and transportation layouts within specific regions.

The traditional gravity model is given by Equation (1):

$$F_{ij} = k\frac{M_i M_j}{D_{ij}^a} \tag{1}$$

In Equation (1), F_{ij} represents the magnitude of gravity between city *i* and *j*; $M_i M_j$ denote the urban masses of cities of *i* and *j* respectively; D_{ij}^a represents the comprehensive distance between city *i* and city *j*, a is the distance decay coefficient, indicating that the larger its value, the faster the decay rate influenced by the distance factor between cities. Typically, *a* is set to 2. The product of distance and cost is used as *D* in the model; *k* represents the gravitational coefficient, which is set to 10^b in this study to make the calculation results more intuitive (Zhao et al., 2021).

Currently, the development of the Greater Bay Area is rapid, primarily relying on highway transportation for logistics within the bay area. Because air, and railway transportation each account for less than 2% of total transportation, thus distances between highways are used as a reference in specific studies. To consider the influence of individual cities, this study calculates the contributions of cities *i* and *j* to gravity, resulting in a revised model as shown in Equation (2).

$$Q_{i\to j} = \frac{M_i}{M_i + M_j} k \frac{M_i M_j}{D_{ij}^a} \tag{2}$$

4.2. Entropy weight method

In the study, we considered the impact of different logistics routes and transportation directions, so we need to take into account the utility of the system in the model based on different starting and ending cities. Entropy method can quantify the contribution of each part to the overall characteristics, thereby evaluating the importance of each part objectively and accurately（Huang，2020）. The study utilizes the entropy weight method to assign weights to indicators, with specific steps as follows:

Step 1: To convert the original data into positive indicators through normalization:

$$X_{ilt} = \frac{x_{ilt} - \min(x_{ilt})}{\max(x_{ilt}) - \min(x_{ilt})} \tag{3}$$

In the equation, X_{ilt} represents the data after positive normalization, x_{ilt} represents the original data of the l-th indicator for city *i* in year *t*, and $\max(x_{ilt})$ and $\min(x_{ilt})$ are the maximum and minimum values of x_{ilt} respectively.

Step 2：To calculate information entropy, we use the method outlined in Equation (4):

$$e_l = -K\sum_{t=1}^{h}\sum_{n=1}^{n}\left[\left(\frac{X_{ilt}}{\sum_{l=1}^{h} X_{ilt}}\right)\ln\left(\frac{X_{ilt}}{\sum_{l=1}^{h} X_{ilt}}\right)\right] \tag{4}$$

In this context, e_l represents the information entropy value; $K = (\ln(h * n))^{-1}$ is a normalization constant; *h* = 11, indicating the total number of years; *n* = 6, representing the number of cities; and 1 denotes the final number of indicators.

Step 3: The coefficient of variation can be calculated based on the information entropy. The calculation formula is shown in Equation (5):

$$y_l = 1 - e_l \tag{5}$$

Step 4: The weight coefficients can be determined. The calculation formula is shown in Equation (6):

$$W_l = \frac{1-y_l}{\sum_{m=1}^{l}(1-y_m)} \tag{6}$$

Step 5: To Calculate the urban comprehensive quality:

$$M_{it} = \sum_{m=1}^{l} W_l x_{ilt} \tag{7}$$

Step 6: To calculate The Urban Gravity Index $P_{i\rightarrow j}$:

$$P_{i\rightarrow j} = \frac{M_i}{M_i+M_j} \tag{8}$$

4.3. Normalize the original data to obtain positive indicators

Zhao et al. pointed out in their study of the Beijing-Tianjin-Hebei region that urban economic total and traffic levels will play a significant role in sustainable urban development (Zhao et al., 2023). Similarly, Gopinath et al. found that GDP is a standard for economic development evaluation in terms of in urban quality. Besides economic development levels, policy directions also guide investment and trade directions. Current policy directions encourage development on the west bank of the Pearl River and green production, thus affecting the flow of social resources such as investment and personnel (Gopinath and Echeverria, 2004).

This article employs a gravitational model, which requires calculating the distance between two cities and the mass of each city to obtain the strength of its attractiveness. To calculate the specific mass of the city, we selected the entropy weight method, taking the economic level of urban development, the level of traffic development, and the level of urban construction into consideration. The indicators are as follows (**Table 2**):

Table 2. Indicators.

Level 1	**Level 2**	**Level 3**
Economic	Urban Economic Aggregate	Regional production total
	Per Capita Possession	GDP Per capita
		Per capita disposable income
Transportation Development	Traffic and Transportation	Traffic mileage
		Passenger Volume
		Freight Volume
Urban Construction	Urban Scale	Urban land area
		Permanent population
	Construction Density	population density
		Per capita green coverage area

- Level 1 indicators: Economic level of cities, level of transportation development, and level of urban construction.
- Level 2 indicators: Economic level includes urban economic aggregate and per capita possession. Transportation development level includes traffic and

transportation, urban construction includes urban scale and construction density.

- Level 3 indicators: Economic total includes regional production total, per capita possession includes per capita GDP, per capita disposable income, Traffic and Transportation includes mileage, passenger volume, freight volume, urban scale includes urban land area, permanent population, construction density includes population density, per capita green coverage.

The distance traversed is represented by costs associated with geographical trade (natural trade costs), costs related to historical and cultural connections, and costs arising from policies (Baier and Standaert, 2020). Field surveys have shown that the costs for cities are primarily natural trade costs, exempt from expenditure of significant historical, cultural, or policy.

The data are quoted from the statistical yearbooks of Shenzhen, Dongguan, Huizhou, Zhuhai, Jiangmen, and Zhongshan, as well as the China Urban Construction Statistical Yearbook from 2012 to 2022. The per capita greening area was indirectly calculated based on the collected statistics.

5. Results found

Using the urban mass calculated by the entropy-weight method and substituting it into the aforementioned formulas, we measured the urban attraction among the six cities in the Greater Bay Area over the past decade. Due to statistical discrepancies, the passenger volume in 2012 was higher than in subsequent years (with Dongguan showing higher figures in 2012 and 2013), leading to urban mass and attraction results that were also higher for that year. Observing the historical data for urban mass (**Table 3**), we find that Shenzhen consistently ranks first among the three eastern cities and all six cities overall. Shenzhen's urban mass has shot up, regardless of slight decline in 2020, while Dongguan, Huizhou, Zhuhai, Zhongshan, and Jiangmen saw modest increases in urban mass prior to 2020 and then urban mass declined thereafter.

Table 3. Urban mass calculation.

Year/City	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Area 5**	**Area 6**
2012	25,114.83255	11,717.79202	6970.90715	4347.034629	6760.866888	4996.78094
2013	7069.739989	11,546.63399	7377.744945	2218.311355	4249.166012	5142.332296
2014	6233.461069	3991.465556	6179.031058	1973.742459	2840.060862	5059.477432
2015	8127.087635	4192.133851	6376.764822	2158.87391	4320.940481	4760.664229
2016	8197.133382	4365.055986	6827.714475	2249.120501	3775.570554	5343.504379
2017	8609.978169	4458.262649	6876.405271	2327.99874	3797.145067	5341.155068
2018	9639.349749	4742.474518	7084.152977	2702.232878	3261.824895	5279.875205
2019	11,610.36564	4806.244452	6604.475829	2538.48111	2827.454391	5138.333853
2020	10,890.6489	4388.148979	5353.403515	2132.962342	2553.841152	4863.793084
2021	11,733.94323	4532.350811	5623.834664	2279.862087	2591.522118	4450.923017
2022	11,425.87097	4305.810428	5355.98532	2081.291183	2742.268137	4306.632458

Note: Number of Area:1: Shenzhen (SZ); 2: Dongguan (DG); 3: Huizhou (HZ); 4: Zhuhai (ZH); 5: Zhongshan (ZS); 6: Jiangmen (JM).

According to the law of gravity, the greater the mass of an object, the greater the gravitational force it exerts. Therefore, by incorporating the calculated urban mass into the revised urban attraction model, we can determine the attraction ranking between cities. The significance of the urban attraction ranking calculated in this paper lies in identifying the direction of attraction between cities, where cities with a higher attraction ranking attract those with a lower ranking.

Based around the urban attraction results and the attraction rankings presented in **Tables 4–7**, it is not hard to find that the attraction outcomes among Shenzhen, Dongguan, Huizhou, and the three western cities. The urban attraction ranking for Shenzhen is significantly higher than that of the three western cities, yet the attraction between Shenzhen and these western cities is quite low.

Table 4. Rate of gravity between eastern-bank cities and western-cities.

Year/City	SZ-ZH	SZ-ZS	SZ-JM	DG-ZH	DG-ZS	DG-JM	HZ-ZH	HZ-ZS	HZ-JM
2012	0.5306	1.7096	0.4486	0.5944	2.2265	0.4791	0.0545	0.1498	0.0459
2013	0.0733	0.2843	0.1468	0.3312	1.4937	0.6324	0.0331	0.1095	0.0660
2014	0.0506	0.1592	0.1135	0.0773	0.2828	0.1653	0.0209	0.0560	0.0466
2015	0.0735	0.3079	0.1530	0.0925	0.4628	0.1887	0.0266	0.0952	0.0553
2016	0.0764	0.2895	0.1614	0.0991	0.4364	0.1995	0.0273	0.0882	0.0574
2017	0.0858	0.3073	0.1737	0.1074	0.4474	0.2073	0.0290	0.0886	0.0585
2018	0.1168	0.2917	0.2018	0.1367	0.3967	0.2251	0.0359	0.0765	0.0618
2019	0.1234	0.2878	0.2360	0.1281	0.3472	0.2335	0.0325	0.0645	0.0618
2020	0.0973	0.2438	0.2095	0.0983	0.2863	0.2018	0.0221	0.0472	0.0474
2021	0.1120	0.2666	0.2066	0.1085	0.3001	0.1907	0.0248	0.0504	0.0456
2022	0.0996	0.2747	0.1946	0.0941	0.3017	0.1753	0.0216	0.0507	0.0420

Table 5. Urban gravity level index from Shenzhen to other western-bank cities.

Year/City	SZ→ZH	ZH→SZ	SZ→ZS	ZS→SZ	SZ→JM	JM→SZ
2012	0.8572	0.1428	0.7959	0.2041	0.8702	0.1298
2013	0.7646	0.2354	0.6368	0.3632	0.6051	0.3949
2014	0.7673	0.2327	0.6869	0.3131	0.5813	0.4187
2015	0.7901	0.2099	0.6529	0.3471	0.6306	0.3694
2016	0.7907	0.2093	0.6762	0.3238	0.6283	0.3717
2017	0.7921	0.2079	0.6900	0.3100	0.6399	0.3601
2018	0.7854	0.2146	0.7542	0.2458	0.6668	0.3332
2019	0.8206	0.1794	0.8042	0.1958	0.6932	0.3068
2020	0.8362	0.1638	0.8100	0.1900	0.6913	0.3087
2021	0.8373	0.1627	0.8191	0.1809	0.7250	0.2750
2022	0.8459	0.1541	0.8064	0.1936	0.7263	0.2737

Table 6. Urban gravity level index from Dongguan to other western-bank cities.

Year/City	DG→ZH	ZH→DG	DG→ZS	ZS→DG	DG→JM	JM→DG
2012	0.7284	0.2716	0.6354	0.3646	0.7497	0.2503
2013	0.8541	0.1459	0.7596	0.2404	0.7342	0.2658
2014	0.6678	0.3322	0.5722	0.4278	0.4584	0.5416
2015	0.6601	0.3399	0.4924	0.5076	0.4682	0.5318
2016	0.6615	0.3385	0.5192	0.4808	0.4664	0.5336
2017	0.6555	0.3445	0.5265	0.4735	0.4702	0.5298
2018	0.6307	0.3693	0.5888	0.4112	0.4829	0.5171
2019	0.6544	0.3456	0.6296	0.3704	0.4833	0.5167
2020	0.6729	0.3271	0.6321	0.3679	0.4743	0.5257
2021	0.6653	0.3347	0.6362	0.3638	0.5045	0.4955
2022	0.6741	0.3259	0.6109	0.3891	0.5000	0.5000

Table 7. Urban gravity level index from Huizhou to other western-bank cities.

Year/City	HZ→ZH	ZH→HZ	HZ→ZS	ZS→HZ	HZ→JM	JM→HZ
2012	0.5717	0.4283	0.4644	0.5356	0.5986	0.4014
2013	0.7604	0.2396	0.6314	0.3686	0.5995	0.4005
2014	0.7465	0.2535	0.6620	0.3380	0.5535	0.4465
2015	0.7471	0.2529	0.5961	0.4039	0.5726	0.4274
2016	0.7449	0.2551	0.6175	0.3825	0.5664	0.4336
2017	0.7360	0.2640	0.6196	0.3804	0.5653	0.4347
2018	0.7088	0.2912	0.6712	0.3288	0.5710	0.4290
2019	0.7224	0.2776	0.7002	0.2998	0.5624	0.4376
2020	0.7151	0.2849	0.6770	0.3230	0.5240	0.4760
2021	0.7115	0.2885	0.6846	0.3154	0.5582	0.4418
2022	0.7202	0.2798	0.6614	0.3386	0.5543	0.4457

Compared to the rest of two cities, Dongguan obtains slightly stronger gravity and Huizhou the least.

In the urban attraction index among eastern cities, Shenzhen proves the highest, which can be noticed in **Table 8**. Meanwhile, we can see that the index between Shenzhen and Dongguan is greater than that between Shenzhen and Huizhou, as well as between Dongguan and Huizhou from **Table 9**. However, the attraction between these cities has remained relatively stable over the past decade, with only minor fluctuations. The urban attraction ranking indicates in **Table 8** that Shenzhen is attracting both Dongguan and Huizhou, while there is mutual attraction between Dongguan and Huizhou as well.

Table 8. Rate of gravity between eastern-bank cities and eastern-bank cities.

Year/City	SZ-DG	SZ-HZ	DG-HZ
2012	102.0154	14.7848	6.7175
2013	30.7737	4.8564	8.9000
2014	7.2897	3.1092	1.9269
2015	10.2293	4.5309	2.3763
2016	10.7090	4.6604	2.4509
2017	11.7006	4.9923	2.5357
2018	14.3045	5.9380	2.8174
2019	16.7543	6.7040	2.8217
2020	14.3486	5.0973	2.0883
2021	15.9677	5.7694	2.2658
2022	14.7713	5.3503	2.0501

Table 9. Urban gravity level index from eastern-bank cities to eastern-bank cities.

Year/City	SZ→DG	SZ→HZ	DG→HZ	DG→SZ	HZ→SZ	HZ→DG
2012	0.6912	0.8181	0.6677	0.3088	0.1819	0.3323
2013	0.3568	0.5059	0.6485	0.6432	0.4941	0.3515
2014	0.6213	0.5283	0.4057	0.3787	0.4717	0.5943
2015	0.6597	0.5603	0.3966	0.3403	0.4397	0.6034
2016	0.6591	0.5640	0.4009	0.3409	0.4360	0.5991
2017	0.6669	0.5774	0.4056	0.3331	0.4226	0.5944
2018	0.6818	0.6005	0.4123	0.3182	0.3995	0.5877
2019	0.7072	0.6374	0.4212	0.2928	0.3626	0.5788
2020	0.7128	0.6704	0.4505	0.2872	0.3296	0.5495
2021	0.7214	0.6760	0.4463	0.2786	0.3240	0.5537
2022	0.7263	0.6808	0.4457	0.2737	0.3192	0.5543

In **Table 11**, the results of urban attraction between western cities show that the attraction between Zhuhai and Zhongshan is the strongest, followed by Zhongshan and Jiangmen, while the weakest is between Zhuhai and Jiangmen. According to the urban gravity index, Zhongshan attracts Zhuhai, while Jiangmen attracts Zhongshan. Additionally, the changes in urban gravity among western cities indicate that since 2019, the gravity between these cities has generally declined which can be noticed in **Table 10**.

Table 10. Rate of urban gravity between western-bank cities and western-bank cities.

Year/City	ZH-ZS	ZH-JM	ZS-JM
2012	239.9552	1.5933	32.9170
2013	73.7298	0.9633	23.9566
2014	40.6486	0.7334	14.7990
2015	67.0550	0.8665	23.2804

Table 10. (*Continued*).

Year/City	ZH-ZS	ZH-JM	ZS-JM
2016	64.5555	0.9106	22.1150
2017	67.9483	0.9717	22.3238
2018	67.1389	1.1756	18.8162
2019	52.9998	1.0997	16.4423
2020	40.2236	0.8746	14.0577
2021	43.6283	0.8555	13.0542
2022	42.1451	0.7557	13.3657

Table 11. Urban gravity level index from western-bank cities to western-bank cities.

Year/City	ZH→ZS	ZH→JM	ZS→JM	ZS→ZH	JM→ZH	JM→ZS
2012	0.3939	0.5277	0.8597	0.6061	0.4723	0.1403
2013	0.3506	0.3205	0.4369	0.6494	0.6795	0.5631
2014	0.3995	0.2963	0.3164	0.6005	0.7037	0.6836
2015	0.3332	0.3120	0.4538	0.6668	0.6880	0.5462
2016	0.3560	0.3091	0.4047	0.6440	0.6909	0.5953
2017	0.3688	0.3181	0.3992	0.6312	0.6819	0.6008
2018	0.4561	0.3535	0.3260	0.5439	0.6465	0.6740
2019	0.4731	0.3307	0.2751	0.5269	0.6693	0.7249
2020	0.4551	0.3049	0.2625	0.5449	0.6951	0.7375
2021	0.4680	0.3387	0.2911	0.5320	0.6613	0.7089
2022	0.4315	0.3258	0.3184	0.5685	0.6742	0.6816

6. Conclusion

We have reached the following conclusions referring to the results of the revised urban gravity model with the entropy weight method as a compensation to evaluation of various indicators.

First, we found that the strongest gravitation pulls both eastern and western cities is between Dongguan and Zhongshan, rather than the traditionally perceived Shenzhen and other west bank cities, which have the highest economic output (Cheng et al., 2023). This finding challenges the stereotype that economic output is the sole determinant of city interactions, highlighting that urban gravity proves to be perplex being influenced by factors such as geographic distance, transportation convenience, and urban development policies (Sinziana and Naima, 2022).

We speculate that this difference engenders because the distance between Dongguan and Zhongshan is shorter than that between Shenzhen and Zhongshan. The strong gravitational force between Dongguan and Zhongshan is due largely to distance and convenient transportation links, because Humen Bridge opening to traffic in 1998 greatly shortened the distance and time between the cities on the east and west sides of the Pearl River estuary. The Humen Bridge connects Dongguan and Guangzhou with extended segment to Zhongshan. And the railway from Dongguan to Zhongshan is further improved. Transport is then of avail from Dongguan to Zhongshan, via railway system from Humen High Speed Rail Station in Dongguan to Zhongshan via

Guangzhou South High Speed Rail Station. Therefore, we also believe that Dongguan and Zhongshan play an important role in connecting the east and west sides of the Pearl River estuary, which also shows that geographical proximity and the level of transportation infrastructure are also crucial for regional economic development. Indicating that they have influence on connecting the eastern and western banks of the Pearl River estuary. This also underscores the importance of geographic proximity and the completeness of transportation infrastructure in regional economic development (Li and Lou, 2023).

Secondly, the gravitational force among eastern cities seems to be the strongest in Shenzhen, and the urban gravity index results indicate that Shenzhen exerts attraction towards Dongguan and Huizhou, reflecting a greater flow of urban resources from Dongguan and Huizhou to Shenzhen, having Shenzhen strengthened as the core of the eastern region in terms of economy. In terms of gravitational interactions among western cities, observations from the urban gravity level index show that Zhuhai has consistently been attracted to Zhongshan, while Jiangmen was attracted to Zhongshan in 2012 and 2013; however, in subsequent years, Zhongshan has been drawn to Jiangmen, and Jiangmen Zhuhai, except in 2012. These results reveal a relatively complex gravitational pattern among the western cities. As an economic special zone, Zhuhai was designed to lead in economic output and urban development among western cities. However, our study reveals that Zhuhai gravitates towards Zhongshan, challenging the traditional view of Zhuhai as the core city of the western region and highlighting Zhongshan’s significant role in regional economic development. According to the data comparison, it can be found that in addition to geographical advantages, Zhongshan also has a higher flow of freights, while the per capita green area also the lowest, indicating that the development route of Zhongshan does not choose to protect a large number of green land like Zhuhai but give priority to the development of secondary industry. We therefore speculate that the attractiveness of west-bank cities is determined primarily by the strength of industry rather than by the quality of life (Ma et al., 2020). Zhongshan not only attracts urban resources from Zhuhai but also influences neighboring cities like Jiangmen to some extent, emphasizing that a city’s relative position and development level are equally important in regional economic working-togethers.

Thirdly, we found that the COVID-19 pandemic has had a salient impact on inter-city communication, leading to a decrease in gravitational attraction in recent years (Wang and Li, 2020). Since the outbreak of COVID-19 at the end of 2019, the pandemic has disrupted both global and domestic economic orders and severely hindered communication and cooperation between cities. In this context, cities have had to implement a series of restrictive measures to curb the spread of the virus. These measures have weakened inter-city connections and interactions to some extent, according to the statistical yearbooks of various cities from 2020 to 2022, the passenger volume of each city has dropped sharply compared to before 2019. For example, in 2019, Shenzhen’s passenger volume reached 212.84 million, but in 2020, after the outbreak of the covid epidemic, Shenzhen’s passenger volume plummeted to 137.5 million, and by 2022, the annual passenger volume had further dropped to 104.39 million. Compared to Shenzhen, the passenger volume of Dongguan dropped from 32.76 million in 2019 to 8.31 million in 2020, and by 2022 it had further dropped to 7.04 million. The decrease in these data has led to a decrease in the attraction between cities, so we can see that the results of the attraction between many cities are lower than in previous years after 2019.

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